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LLNL-CONF-657924

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R. Leach, A. Awwal, E. Bliss, R. Roberts, M. Rushford, K. Wilhelmsen, T. Zobrist

July 31, 2014

SPIE Optics and Photonics Conference
San Diego, CA, United States
August 17, 2014 through August 21, 2014

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Optics and Photonics for Information Processing VII

Part of the SPIE International Symposium on Optical Engineering + Applications
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Analysis of the Confluence of Three Patterns Using the Centering and Pointing System (CAPS) Images for the Advanced Radiographic Capability (ARC) at the National Ignition Facility

Richard R. Leach Jr., Abdul Awwal, Erlan Bliss, Randy Roberts, Michael Rushford, Karl Wilhelmsen, Thomas Zobrist

Integrated Computer Control System, National Ignition Facility
Computational Engineering Division
Lawrence National Laboratory, Livermore, CA 94551
e-mail: leach1@llnl.gov

ABSTRACT

The Advance Radiographic Capability (ARC) at the National Ignition Facility (NIF) is a laser system that employs up to four petawatt (PW) lasers to produce a sequence of short pulses that generate X-rays which backlight high-density internal confinement fusion (ICF) targets. Employing up to eight backlighters, ARC can produce an X-ray "motion picture" to diagnose the compression and ignition of a cryogenic deuterium-tritium target with tens-of-picosecond temporal resolution during the critical phases of an ICF shot. Multi-frame, hard-X-ray radiography of imploding NIF capsules is a capability which is critical to the success of NIF's missions. The function of the Centering and Pointing System (CAPS) in ARC is to provide superimposed near-field and far-field images on a common optical path. The Images are then analyzed to extract beam centering and pointing data for the control system. The images contain the confluence of pointing, centering, and reference patterns. The patterns may have uneven illumination, particularly when the laser is misaligned. In addition, the simultaneous appearance of three reference patterns may be co-incidental, possibly masking one or more of the patterns. Image analysis algorithms have been developed to determine the centering and pointing position of ARC from these images. In the paper we describe the image analysis algorithms used to detect and identify the centers of these patterns. Results are provided, illustrating how well the process meets system requirements.

Key words: Advanced Radiographic Capability (ARC), Optical alignment, confluence, image processing, image analysis, National Ignition Facility (NIF),

*This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

1. INTRODUCTION

The National Ignition Facility at the Lawrence Livermore National Laboratory has been operational since 2009 for the study of high-energy density and fusion science. A primary goal for NIF is that of achieving ignition, which is to produce a net energy gain for the first time in a laboratory setting [1-3]. To achieve this goal, we have built a 1.8 MJ ultraviolet laser system consisting of 192 beams, capable of delivering up to 500 trillion watts of power onto a 2mm diameter target.

Experiments and operation of the National Ignition Facility (NIF) will soon utilize high-energy x-ray back lighters. In March 2014, NIF began deployment of a vital diagnostic named ARC (Advanced Radiographic Capability) which is designed to generate precise, high-energy short-pulses [4-7]. Using up to eight backlighers, ARC will provide X-ray images at critical phases of internal confinement fusion

(ICF) shots. The alignment precision for ARC's Centering and Pointing System (CAPS) is a vital element in the successful operation of the ARC system.

2. ADVANCED RADIOGRAPHIC CAPABILITY CENTERING AND POINTING SYSTEM

The function of CAPS is to capture superimposed near-field and far-field images on a single imaging camera. The Images are then analyzed to extract beam centering and pointing data for the ARC control system. The images contain the confluence of pointing, centering, and reference patterns. Image analysis algorithms have been developed to determine the centering and pointing position of ARC from these images.

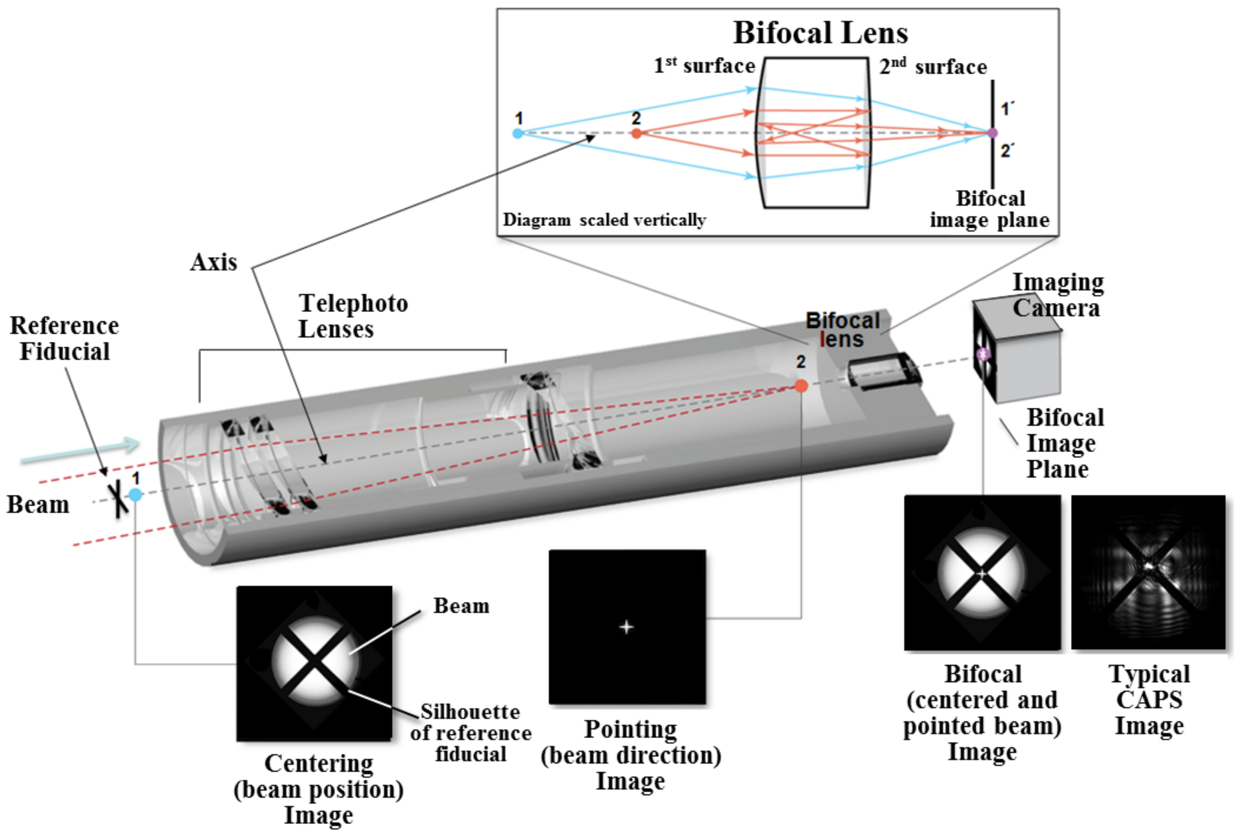

Figure 2.0 CAPS uses a bifocal lens in a single optic tube to achieve simultaneous pointing and centering in the ARC alignment system.

Precise alignment of a laser beam involves adjusting the beam's position within the component apertures through which it passes, as well as sending the beam in the correct direction toward the target. To achieve alignment the beam must intercept two fixed points in space. The first point determines if the beam is centered in its path, while the second determines if the beam is pointed in the right direction.[8-10] In most conventional laser-beam alignment systems, a sensor is needed at each alignment point to relay that information to the beam control system. These two alignment sensors are typically mounted separately, each with its own camera. Other systems use a single optic system and camera, in which case a centering lens is used for the centering adjustment and is then exchanged for a pointing lens where a second adjustment is made. CAPS produces the output of both sensors simultaneously using a single, mechanically simple, optic tube. It uses a single bifocal imaging lens to view both pointing and centering points, combining and transmitting the information to one camera. The image contains both the centering and pointing data needed to align the beam. In addition, CAPS is monolithic, formed in a single piece with no moving parts. This can provide substantial advantages in stability and repeatability over conventional alignment systems. The diagram in figure 2.0 describes the CAPS system in further detail.

Figure 2.1 illustrates the beam paths and main optics for the ARC compressor vessel, path to the diagnostic package, and path to the NIF Target Chamber Center (TCC). Mirrors labeled AM1-AM4 direct laser pulses from a NIF beamline into the ARC compressor vessel. The compressor vessel, shaded in blue in the figure, contains gratings labeled G1-G4 and other optics used to assess the alignment of the gratings. The gratings compress the pulse into its final shape before propagation into the NIF TCC. The compressed pulse leaves the compressor vessel at AM5 and is split along two paths. A small fraction of the pulse's energy is directed towards a diagnostic package using mirrors DM1-DM9. This section of the ARC is shaded in green in the figure. The remainder of the pulse is directed towards the NIF TCC using AM5-AM8. This section is shaded in red in the figure. The diagram includes references to the centering and pointing loops used to align the optics. Boxes labeled 'PC,' for pointing and centering, indicate the position of the cameras used in the alignment loops. Arrows emanating from the boxes indicate which mirrors are controlled by particular alignment loops. For example, the cameras for CAPS are located between mirrors AM6 and AM7, and control AM5 and AM6 to center and point the beam into parabolic mirror AM7.

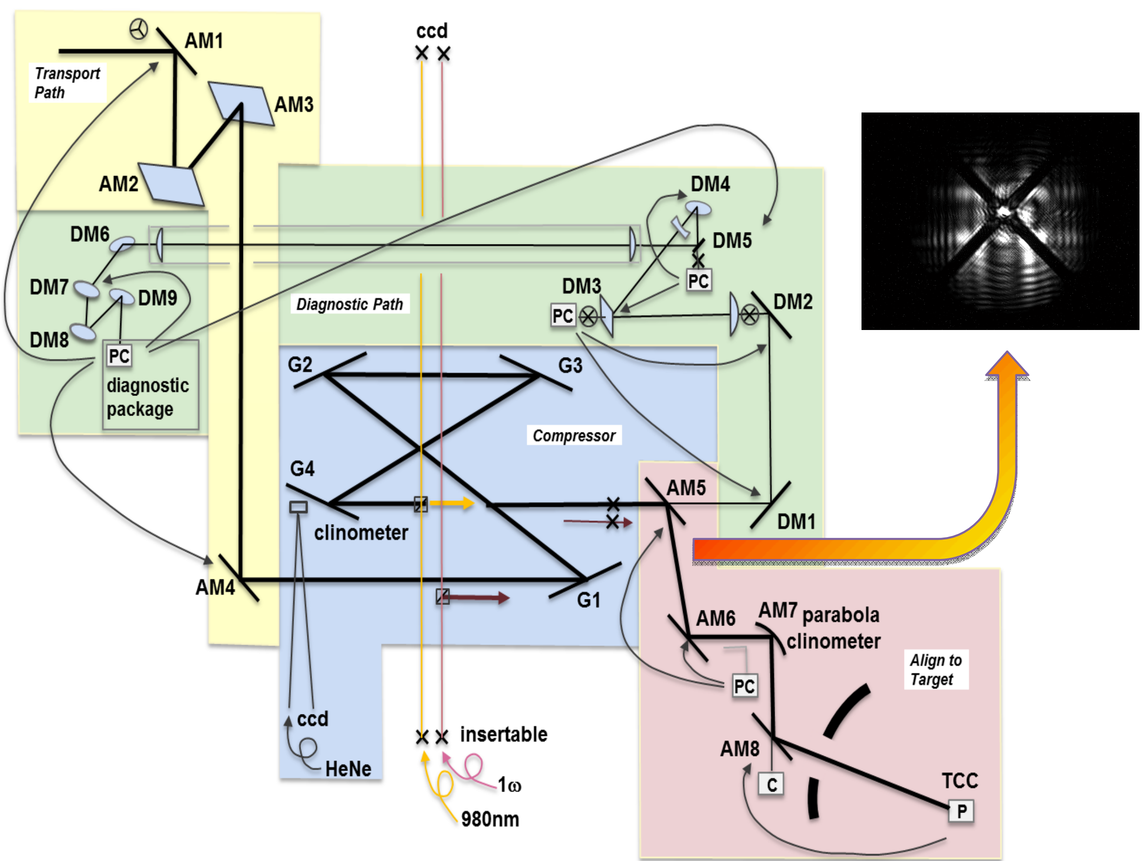

Figure 2.1 Diagram Showing the location of CAPS in the ARC alignment system.

3. CONFLUENCE OF THREE PATTERNS IN CAPS IMAGES

Using a single optic tube has several advantages, including size, simplicity, and mechanical stability. This system, however, produces complex images which contain critical alignment features. The CAPS images contain a confluence of three features or patterns, each providing in turn the reference, pointing, and centering location of the beam. This presents challenges to processing the CAPS images. Non-targeted patterns can be viewed as contributors to overall image noise when trying to identify a target pattern. The patterns may also have uneven illumination, particularly when the laser is misaligned. In addition, the simultaneous appearance of three reference patterns may be co-incidental, possibly masking parts of one or more of the patterns.

When locating multiple patterns in an image where there is some systematic knowledge such as sizes or locations of patterns, one effective method is to process the image in stages. We begin by processing the least difficult pattern. Knowledge obtained from the first stage is stored and utilized in the later stages. Using this approach, processing for CAPS begins with locating the center of the pointing beam in the first stage, then continues by locating the center of the reference fiducial pattern in the second stage, and finishes by locating the center of the centering beam to complete the alignment image processing. An example of a CAPS image is shown in Figure 3.0 where the pointing beam appears as the small, bright peak in the lower left portion of the image.

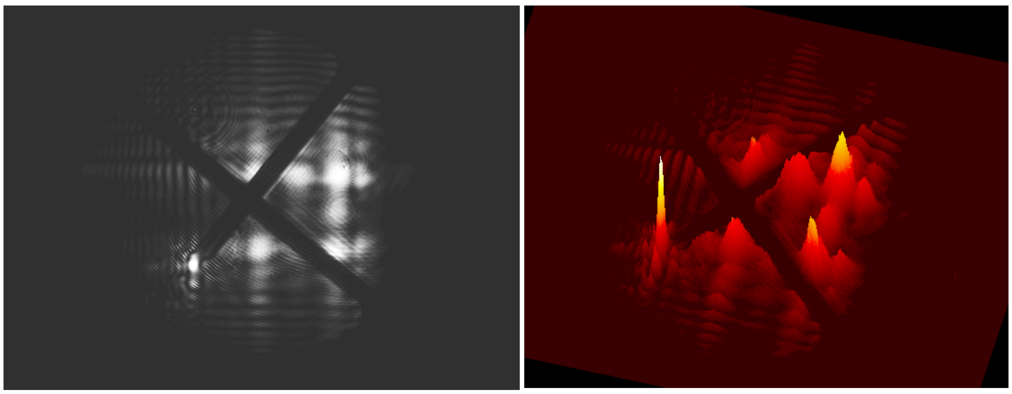

Figure 3.0 CAPS images contain the confluence of 3 patterns. In this example, the image is on the left and the surface plot of the same image is on the right. The pointing beam is the bright, tall peak and appears the lower left portion of the surface plot

3.1 Pointing Image Pattern

The pointing beam pattern is typically the brightest spot in the image. The full width half maximum (FWHM) value is on the order of 15 to 20 pixels and appears as a bright white dot in the image when CAPS is aligned. Successful alignment requires that the center of the dot coincides with center of the intersection of the two dark, diagonal bands in the image. As pointing moves away from alignment, the FWHM value can increase and the intensity can drop significantly. As illustrated in figure 3.1, the pointing pattern image processing produces the estimate (x_p, y_p) of the location of the center of the spot.

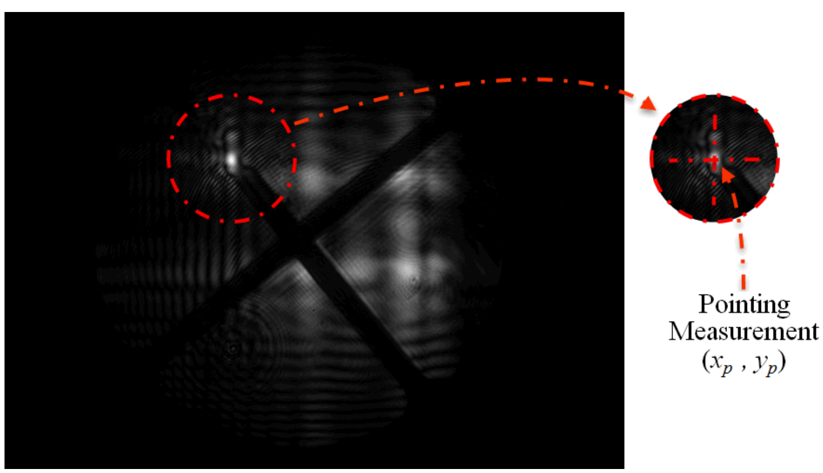

Figure 3.1Pointing pattern is measured by estimating the pixel location (x_p, y_p) of the center of the bright spot in the CAPS image.

3.2 Centering Image Pattern

The centering beam pattern is a medium bright, somewhat diffused crosshatch pattern that can appear throughout the image. The nominal size of the pattern is fixed, however the pattern can be masked by the dark, diagonal reference lines as well as the pointing beam. As seen in figure 3.2, the centering pattern image processing produces the estimate (x_c, y_c) of the location of the center of the patch.

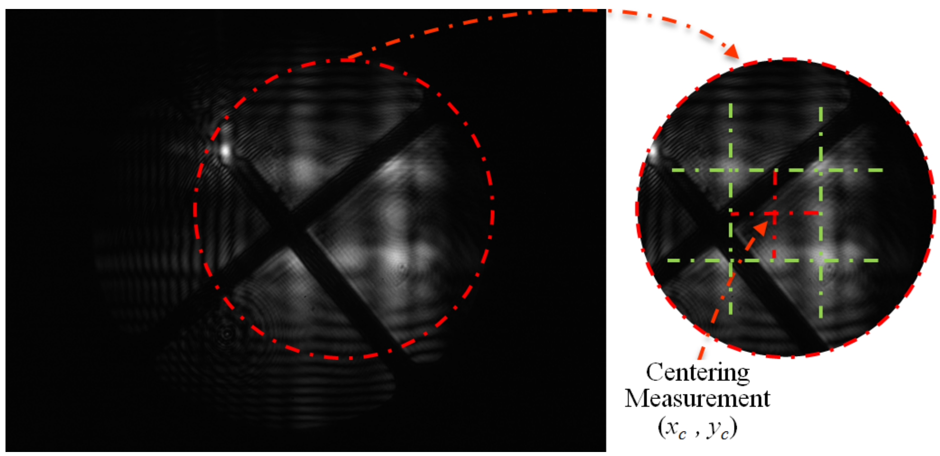

Figure 3.2Centering pattern is measured by estimating the pixel location (x_c, y_c) of the center of the crosshatch patch in the CAPS image.

3.3 Reference Image Pattern

The reference pattern consists of two dark, diagonal lines that appear in the image. The nominal line width is fixed, however the edge contrast vary along the lines as well as from image to image. Changes in illumination along the lines and sharpness of the edge can vary significantly. As seen in figure 3.3, the reference pattern image processing produces the estimate (x_r, y_r) of the location of the center of the intersection of the two lines.

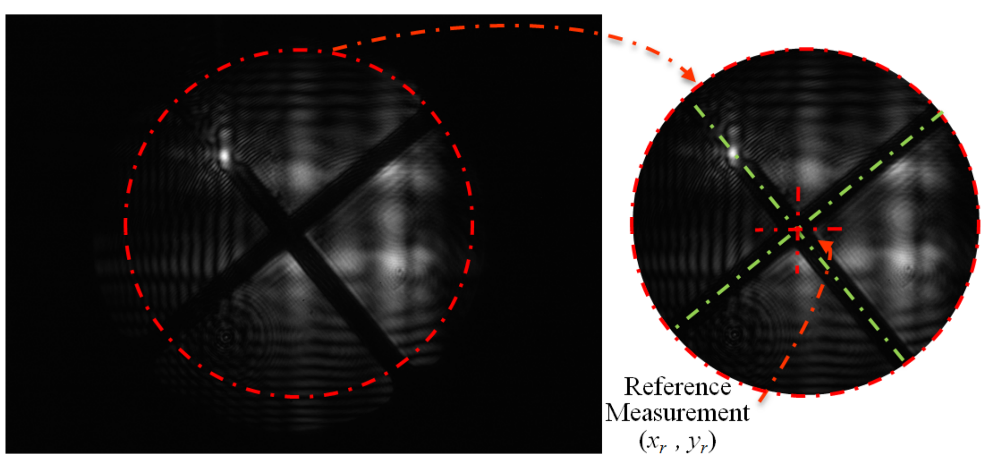

Figure 3.3Reference pattern is measured by estimating the pixel location (x_r, y_r) of the center of the intersection of the two dark, diagonal lines in the CAPS image.

4. IMAGE PROCESSING AND ANALYSIS

4.1 Off-normal image conditions

A pre-requirement for proper alignment is to test each input image for off-normal conditions [12] including blank images, dim images, saturated images, incorrectly sized images and images with incorrect bit depth. Images that fall into one of these categories are flagged, automatic alignment ends, and an operator intervenes. Normally, all of these tests are passed and alignment begins. Figure 4.1 illustrates some of the off-normal image conditions that are monitored by the system.

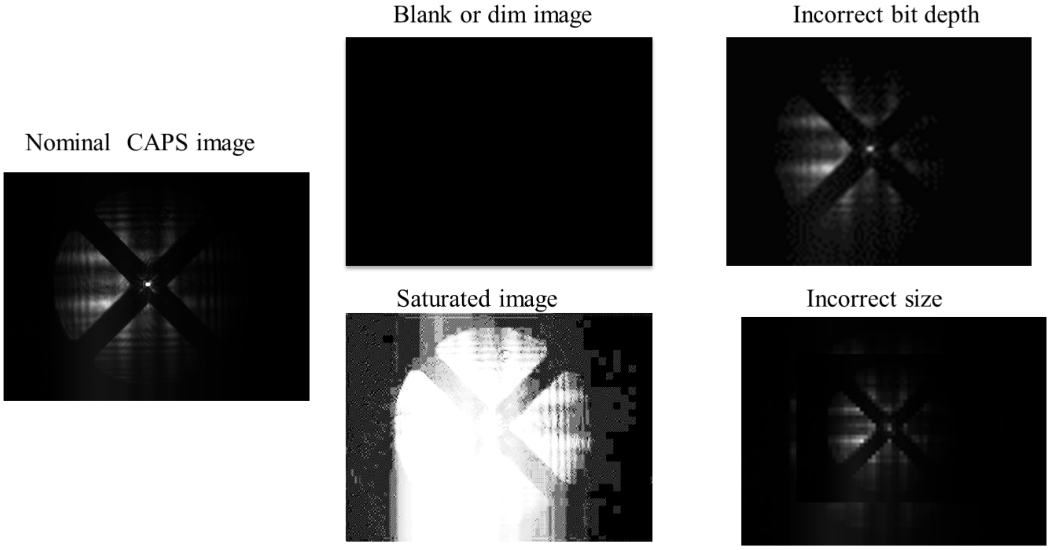

Figure 4.1System monitors images for off-normal conditions including images that are blank, dim, or have incorrect bit depth or image size

4.2 Pointing Beam Image Processing

The pointing beam pattern is most often, but not always, the brightest spot in the image. For the initial position estimate, all regions in the image are first labeled and then filtered by size whereas the regions that exceed a minimum of area are considered pointing beam candidates. Figure 4.2 illustrates the process in greater detail.

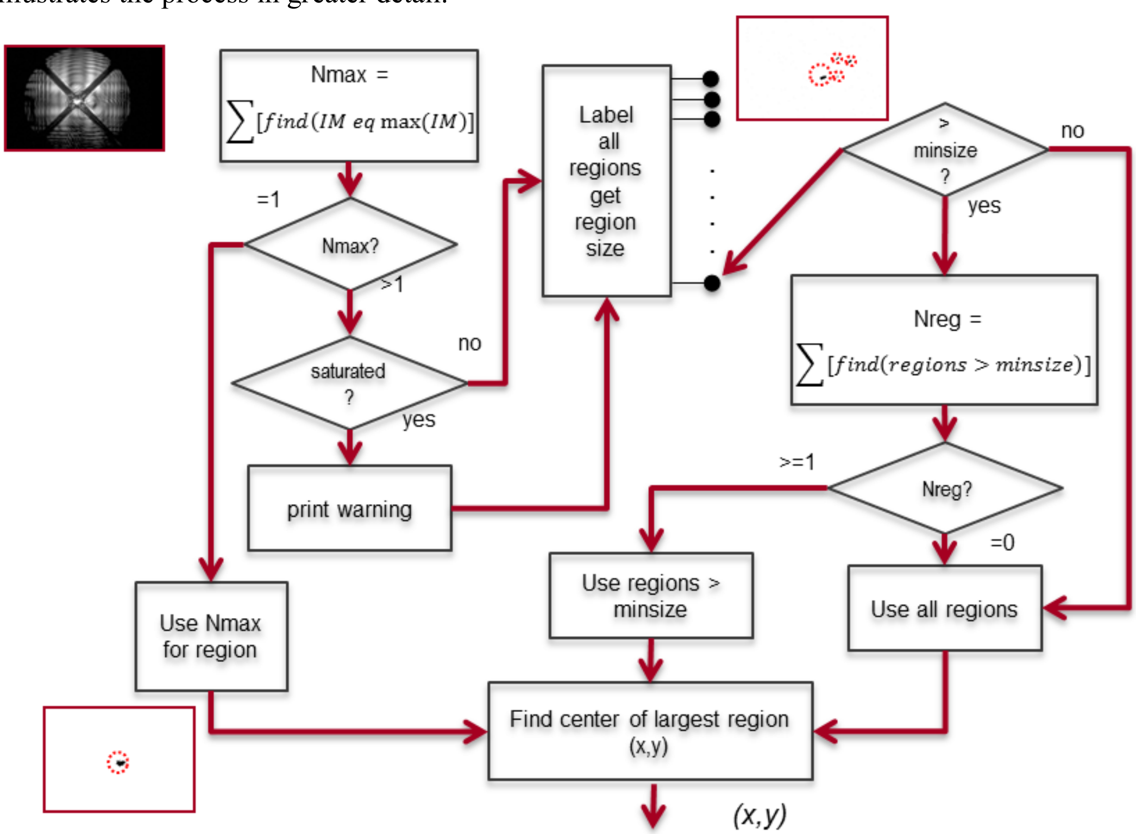

Figure 4.2 Initial pointing beam centers are obtained by labeling all regions and then applying a region size and intensity filter to locate the initial pointing beam candidate location (*x, y*).

Centers (x,y) obtained by this process are at the location the brightest pixel in the filtered region. To determine the center of the pointing beam center more precisely, a set of pixels surrounding the local area of (x,y) and exceeding an intensity threshold are used to calculate a weighted centroid. Each pixel in the image is evaluated according to the following criteria resulting in a pointing beam location estimate (x_p,y_p).

First, the image containing m rows and n columns can be represented by matrix A.

$$A = \left(a_{ij}\right)_{m\times n}$$

Next the matrix of distances D is are calculated for all pixels to the center (x,y) found previously.

$$d_{ij} = \sqrt{(i-x)^2 + (j-y)^2}$$

We then define an intensity threshold I_{th} from the intensity value a_{xy} at the brightest pixel (x,y) in a selected region based on its size and intensity.

$$I_{th} = \frac{\sqrt{2}}{2} \times a_{xy}$$

Using a nominal beam radius value r_{nom}, all pixels where d_{ij} exceeds r_{nom} and a_{ij} is greater than I_{th} are used to measure a weighted centroid estimate (x_p,y_p) for the location estimate of the pointing beam with the following formula.

$$\begin{bmatrix} x_p \\ y_p \end{bmatrix} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} a_{ij}\begin{bmatrix} x_i \\ y_j \end{bmatrix}}{\sum_{i=1}^{n}\sum_{j=1}^{m} a_{ij}}$$

4.3 Reference Fiducials Image Processing

The Crosshairs Algorithms [11] is used to locate the center of the reference pattern which appears as two diagonal dark bands in the image. This algorithm is commonly used in NIF for line and edge estimation where automatic alignment requires precise location of line objects. Images are first rotated so that the target line is vertical in the image.

The algorithm then segments the image into horizontal bands which are then compressed to 1D signals by taking a measure across the band. In this case we use the mean to form a set of signals, one for each band. The signals are then processed to yield a line or edge detection per band. This provides a set of points that can be evaluated, culled for outliers, and undergo a linear fit to produce the final line estimate. Figure 4.3.1 illustrates the segmentation and signal processing in the algorithm for a NIF target chamber beam alignment image.

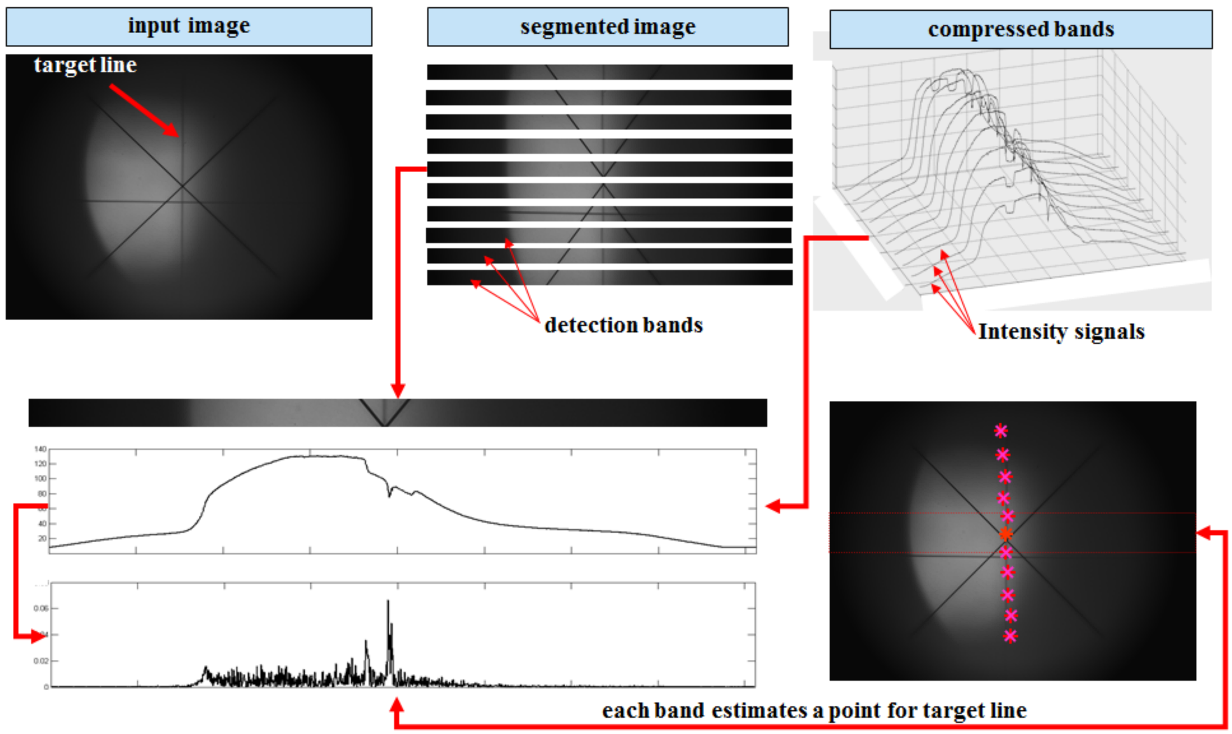

Figure 4.3.1 Crosshairs algorithm segments image into horizontal detection bands which are compressed and processed to provide a set of candidate edge points for each line.

Reducing the image to a 1D signal processing task is computationally efficient and works well for large images. The segmentation or banding is tolerant to images with noisy, partially hidden, or sparse edges. Figure 4.3.2 illustrates how a lower contrast line is detected from nearby higher contrast lines.

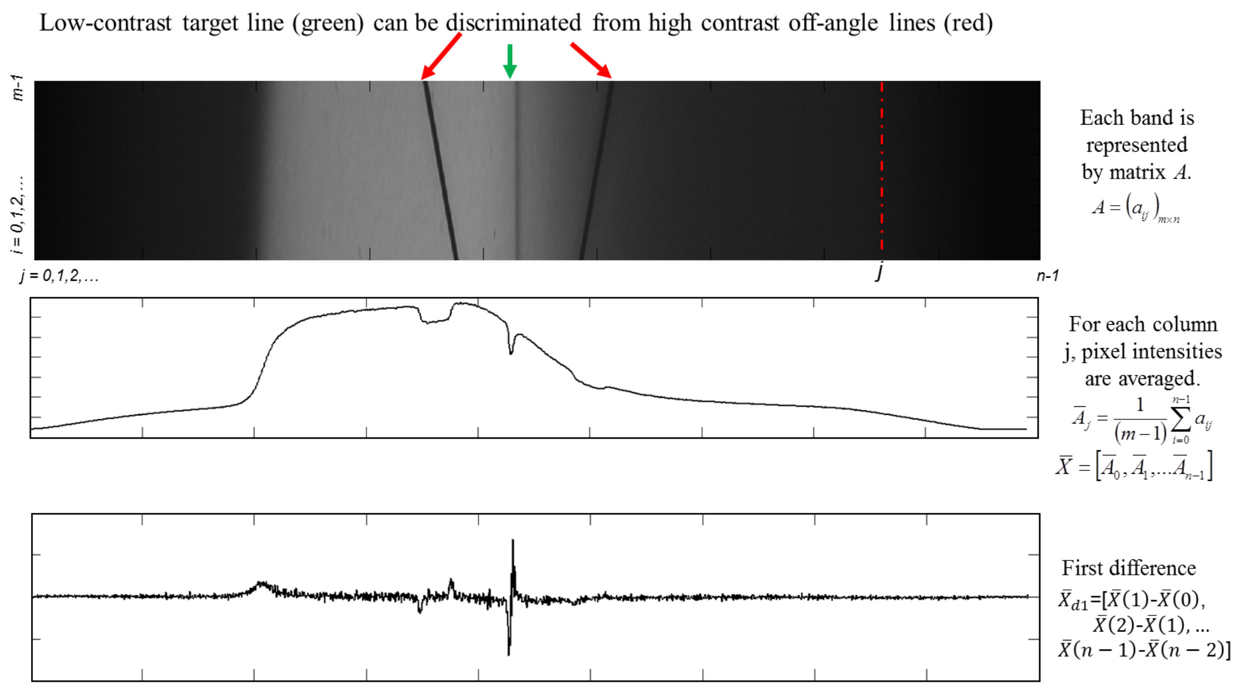

Figure 4.3.2 Example of the crosshairs algorithm finding a lower contrast line. The band (top) is compressed to form a (middle) signal and then processed (below) to emphasize the higher slope of the vertical line.

After processing the complete set of bands, outliers are culled using nominal line thickness, mean intensity, deviation from line fit, and nominal spacing parameters. The remaining set of points is used to create a binary image by setting their pixel location in the image to one with zeroes elsewhere. This image is then processed with a linear Hough transform to calculate the line fit. In the first and second panels, figure 4.3.3 shows the results with a CAPS image and the points found on the rotated image. The results from the pointing beam measurement were used to mask the region around the pointing beam due to its brightness. Due to the masking, points were not found along the line near the location of the pointing beam. Regardless, a small set of correctly identified edges from the bands with good contrast yields good results. This can be seen in the right panel which is the accumulator space of the Hough transform, where the peak has little ambiguity, producing an optimal line fit.

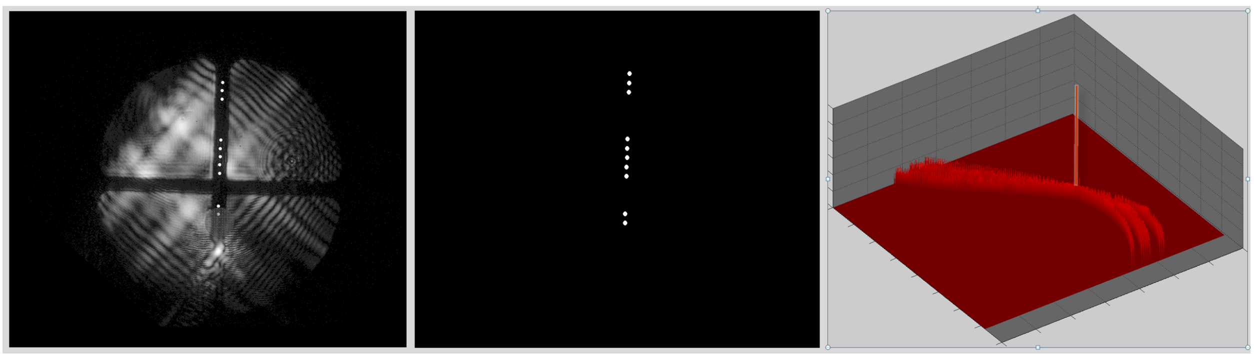

Figure 4.3.3 Example of line fitting using the Hough Transform. CAPS image on the left have a set of edge detections used to create binary input (center). The resulting accumulator space yields high certainty of an accurate line fit to the data as seen in the high sharp spike (right)

4.4 Centering Beam Image Processing

The centering beam pattern is a complex pattern that is the result of light that has been significantly diffracted before it is recorded at the camera. We take advantage of several characteristics of the diffraction pattern, including its size, constant rotational position, and the 4 orthogonal bright streaks within the pattern. With this information a filtered projection of the mean of the rows and columns in the image are used to isolate and emphasize the bright streaks in the horizontal and vertical direction.

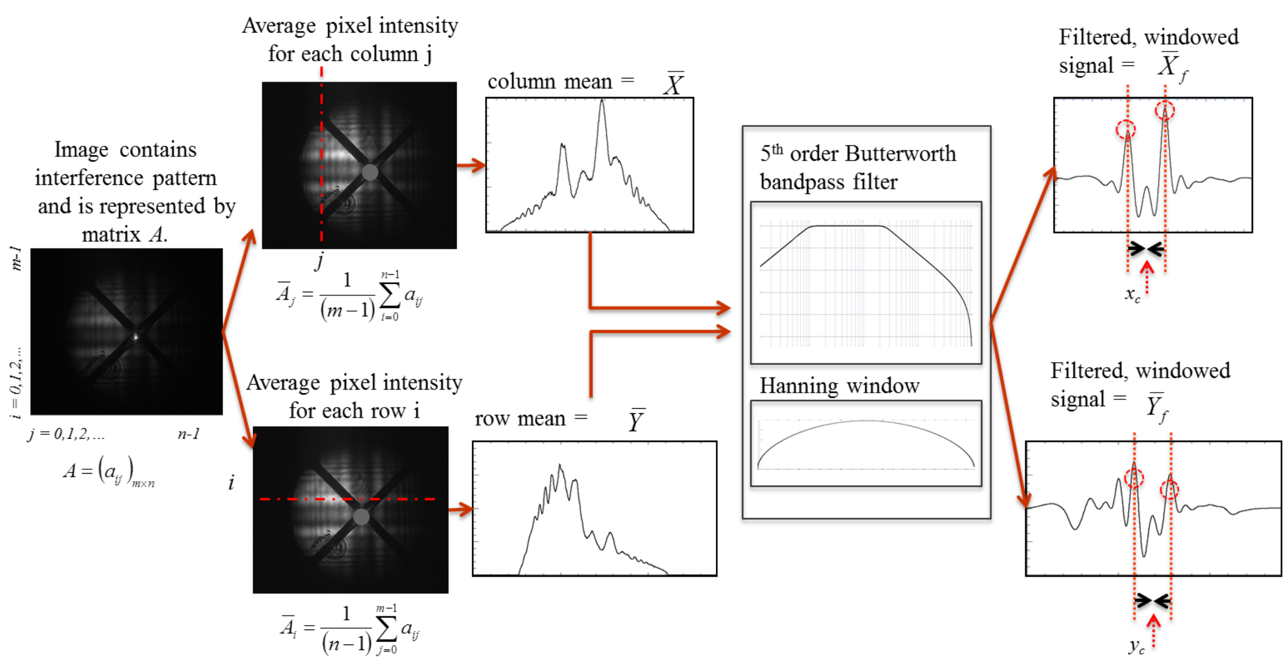

Figure 4.4 Centering beam centers are obtained using filtered projection to produce vectors of row and column means. Measurement of dominant peaks using nominal spacing provides the centering location estimate (x_c, y_c). Note the masking of the pointing beam in the images.

The mean location of the resulting peaks provide the location of the center of the centering beam (x_c,y_c). Details of this process are found in figure 4.4 where the pointing beam and its local area have been masked out to reduce interference with the centering beam measurement.

4.5 Results and Analysis

Figure 4.5.1 illustrates several examples of images reflecting aligned, or nearly aligned, beams in the CAPS system. Beginning March 2014, ARC began providing images like these for algorithm development and testing. Previous development was done using synthetic images produced by modeling codes. The images seen in (a), (b), (d), and (e) are the some of the most recent images produced by the ARC CAPS system. (June 2014).

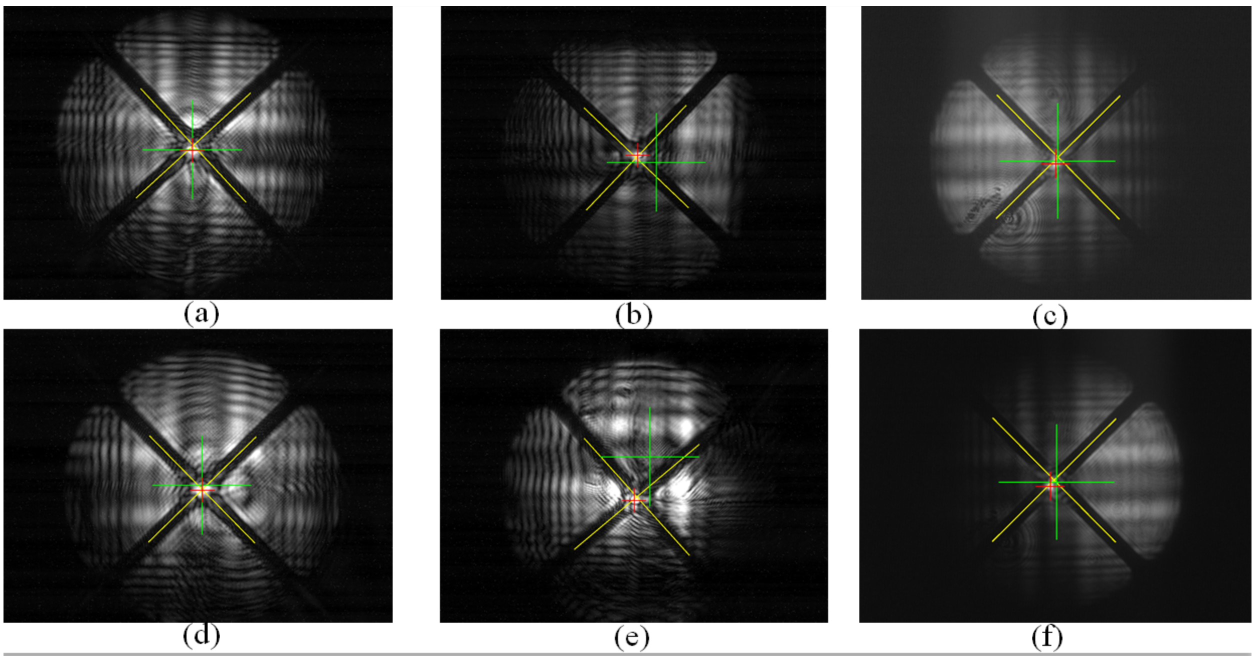

Figure 4.5.1 Examples of aligned or nearly aligned pointing and centering positions in CAPS. The image processing results for the pointing location (red), the centering location (green), and the reference (yellow) are superimposed. Both (a), (d), and (c) are within a few pixels of exact alignment.

Figure 4.5.2 illustrates several examples of images reflecting mis-alignment in the CAPS system. Images representing near alignment conditions as seen in Figure 4.5.1 have a higher confidence for successful processing for both pointing and centering. However, to test the CAPS image processing alignment algorithm, the pointing and/or centering beam were intentionally mis-aligned. It was discovered that as alignment worsens, several issues arise. For example in 4.5.2 (b), the centering pattern is partially clipped by the tube aperture. The centering measurement was successful in this case 4.5.2 (b), since enough of the filtered and projected signals were unclipped and allowed for the correct peak identification. An increase in clipping beyond this example would prevent measurement of the centering pattern. ARC alignment is unlikely to experience this condition, however, during normal operation.

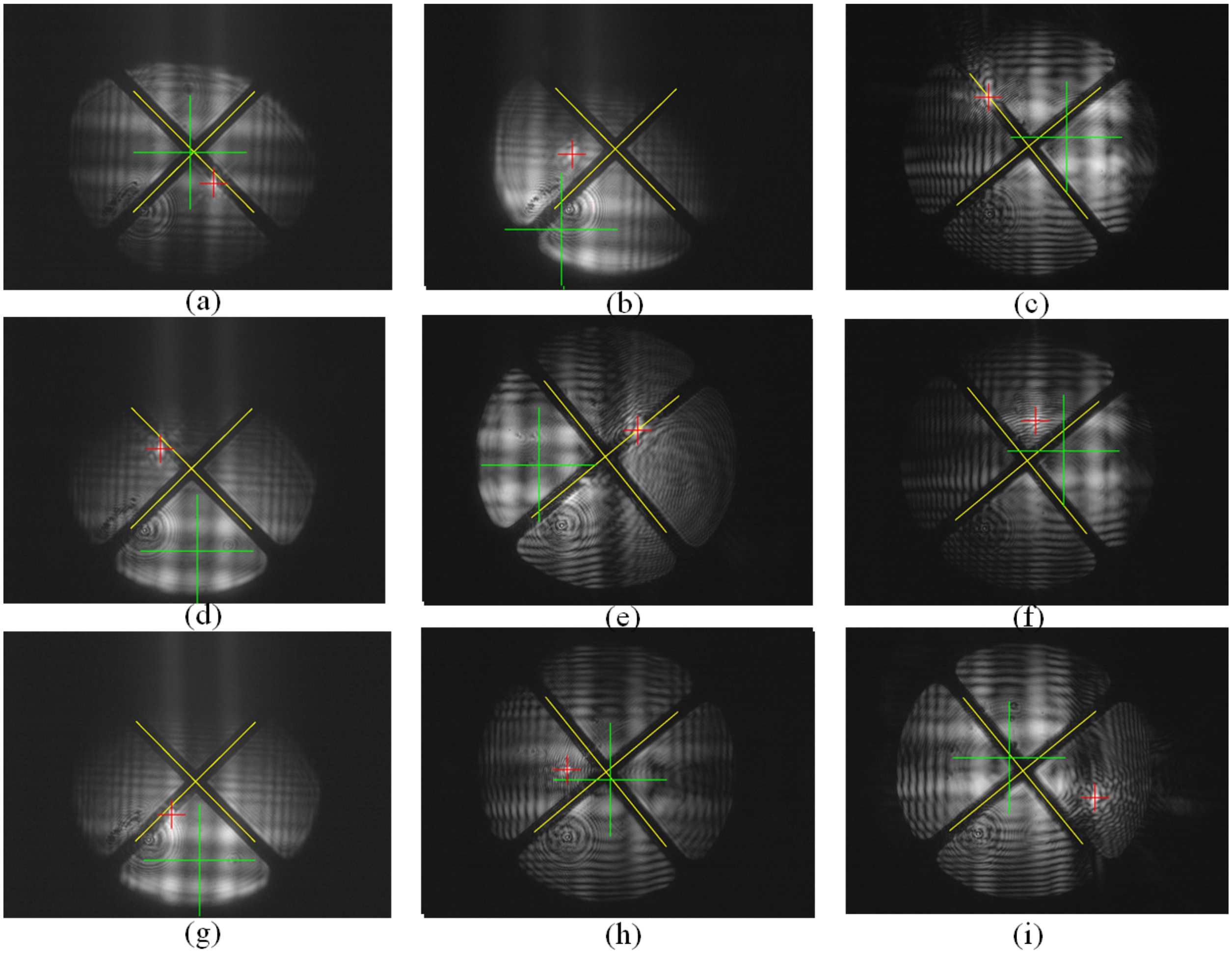

Figure 4.5.2 Examples of mis-aligned pointing and centering positions in CAPS. The image processing results for the pointing location (red), the centering location (green), and the reference (yellow) are superimposed.

Another issue comes into play regarding the centering diffraction pattern. The pattern consists of mottled, white streaks, but also has four bright spots near its center. When mis-alignment occurs, one, or more of these spots can be mistaken for the pointing beam. This can be seen in (g), where the pointing beam is nearly coincident with the upper left spot in the centering pattern. To mitigate this potential condition, a final, automated processing step in the algorithm is performed to measure the distance of the initial pointing beam location to the center of each of the four bright spots. If they coincide, the spots are masked and the pointing beam is re-measured using the masked image.

5. SUMMARY

In this paper we described the development of a new Advance Radiographic Capability (ARC) at the National Ignition Facility (NIF) and the function of the Centering and Pointing System (CAPS) which is to provide superimposed near-field and far-field images on a common optical path. Image processing algorithms to process CAPS images containing the confluence of three patterns were described in detail including the pointing, centering, and reference measurements. Results were also presented, including illustrations of image processing results for both aligned and mis-aligned conditions.

ACKNOWLEDGEMENTS

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. The authors would like to thank Alan Conder and Tom McCarville for their assistance in providing CAPS data and images. We would also like to thank Alan Conder and Jose E. Hernandez for their many helpful comments.

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